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Design and vehicle integration challenges for autonomous vehicle LIDARs

Executive summary

With announcements from a large number of automakers to commercialize autonomous cars by 2021, number and variety of sensors in vehicles are poised to grow significantly posing new challenges for vehicle engineering for automakers and suppliers. At the same time, designing for harsh automotive environments with significantly higher reliability and safety requirements is a new challenge for many electronics companies who have an opportunity to disrupt the automotive industry. Design, performance and reliability of LIDARs, a key sensor critical to offer a robust 360° vision to autonomous cars, are impacted by its thermal behavior. Simcenter's electronics thermal characterization and simulation tools and their connectivity with electronics design and layout software offer the functionality and accuracy of simulation that engineers can rely on to address such challenges.

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Introduction

Reliable and cost-effective 360° vision creation, enabled by various vision and non-vision sensors, is at the heart of development and commercialization of autonomous vehicles. With the strong push for ADAS and autonomous vehicles, sensor market is projected to grow from $3 billion in 2015 to $35 billion by 2030 [1]. One of the key autonomous functionality-enabling sensor is LIDAR (Light Detection and Ranging) that was first used in the concept vehicles competing in DARPA (Defense Advanced Research Project Agency) Grand Challenge for autonomous vehicles [2]. LIDARs rely on time of flight measurement for emitted light from laser diodes to be detected by receivers after reflecting back from objects in its path, and thus provide highly accurate information not only about object distance but also offer 3D information on object width and height.

One of the early pioneers of LIDAR technology is Velodyne that introduced mechanical rotating LIDARs to offer 360° vision. The mechanical rotating LIDARs are the most distinguishing visible hardware on the vehicle bodies for the autonomous test fleet on the road today. Although such LIDARs provide 360° view with very high resolution and long range (up to 200 m), high cost is a key deterrent for these LIDARs to be part of commercially-viable autonomous vehicles. Although in recent years, some companies, most notably Waymo [3], have made significant advances to significantly reduce cost of these mechanical rotating LIDARs. Additionally, large size and potential reliability issues due to mechanical parts, pose additional challenges for vehicle integration. Due to these issues, industry is moving towards solid-state LIDARs which promise to be in the $100-$250 LIDAR price point at large scale volume. Solid-state LIDARs don't have costly electric motors as used in mechanical rotating LIDARs thus offer more cost-effectiveness but suffer from limited field of view (FoV) and lower range/resolution. Multiple solid-state LIDARS will be needed to be integrated in autonomous vehicle. A large number of companies developing solid-state LIDARs are pursuing innovative emitter/detector technologies to improve range and resolution as well as component and functionality consolidation to achieve desired miniaturization.

Design goals for LIDARs (solid-state or mechanical rotating ones) are largely centered on size and cost reduction without sacrificing (or increasing) range and resolution. Increase in optical power benefits LIDAR range whereas integration of multiple light emitters and detectors on single monolithic chip sets and higher signal processing improves resolution. These design factors combined with desired small form factors may cause significant heat buildup that may be detrimental to performance and durability of LIDARs. This may deter LIDAR size (and cost) reduction efforts. Additionally, LIDARs when integrated in vehicles must function reliably in an automotive environment and in all-weather conditions. Vehicle mounting location may further present additional thermal challenges that sensor designers will need to account for while designing sensors. The fact that different auto makers are looking to integrate LIDARs in different parts of vehicle body, for instance side bumpers, front grill, headlights or taillights etc, further enhances design complexity for sensor vendors.

This white paper is aimed at highlighting thermal-driven design challenges for LIDARs as well as impact of vehicle integration strategy on reliability in real-world operation. Underlying thermal issues resemble that in any consumer electronics, however, for LIDARs and other autonomous vehicle sensors unique challenges arise because of much harsher automotive environment and the associated reliability and safety issues with these sensors. We'll showcase how Simcenter's EDA-centric electronic cooling simulation software can be exploited by sensor vendors and Auto OEMs alike to account for these challenges. For sake of consciousness, we'll take a generic solid-state LIDAR example but the challenges highlighted here apply equally to mechanical rotating LIDARs as well. Key takeaway message for readers is that thermally-conscious designs for LIDAR signal processing electronics as well as for their enclosures, while taking into account their vehicle integration locations, is critical to ensure desired size, cost, performance and life goals are met.

Thermal-driven challenges for solid-state LIDARs

Thermal design of electronic systems in automotive applications, such as LIDAR, present common as well as a number of unique challenges. Any thermal design of electronic systems involves ensuring that the critical IC components operate within the specified temperature ranges allowing the system to provide sustainable and reliable performance. Thermal design of electronic systems that are deployed in locations that allow for human contact must also include the outer enclosure temperature as a design constraint to prevent harm when touched. There are situations where the external temperature is further limited by a perceived rather than the safe touch temperature. If an external surface seems too warm this might lead the end user to consider the system to be malfunctioning or even poorly designed. Additionally, accurate LIDAR thermal analysis is critical because the measured distance vary with operating temperature and require temperature compensation [4]. For LiDAR systems that use custom SoC (system on chip) ICs it is essential to predict operating temperature and temperature gradients that contribute directly to reliability. The operating temperatures of both the internal IC components and external surfaces are influenced by the internal heat generation of IC components, incident solar loading, surrounding temperature and air flow, and the thermal design.

Thermal design begins well before any prototyping and ideally when the system is first architected. If thermal design is considered prior to, and in parallel with electrical and mechanical, the overall design process is shortened and results in a more robust product design. Thermal analysis early in the design process can quickly eliminate some options while indicating what designs show promise. Figure 1 shows a conceptual thermal model used to explore design variables such as component layout.

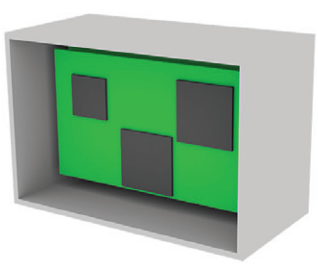


Figure 1: Pre-CAD model of LIDAR system.

As the electrical and mechanical design evolves, the thermal design is refined in parallel to provide clear indication to what designs should be prototyped and tested. During this phase, Simcenter's thermal simulation tools and its seamless connectivity with electronics design tools (e.g. Simcenter's Xpedition) and mechanical CAD environment can be used for detailed thermal analysis [5]. Figure 2 shows the thermal model of a prototype candidate later in the electrical and mechanical design phase.

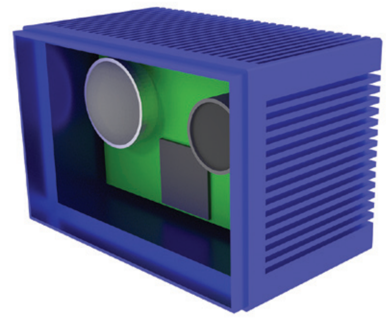


Figure 2: Post-CAD model of LIDAR system with detailed components on PCB.

In addition to thermal design exploration and optimization for a LIDAR, it is important to evaluate design and reliability implications for wide range of vehicle integration and use case scenarios. For instance, vehicle-mounted LIDAR in hot sunny day where solar radiation can be a significant factor for heat buildup or potential contribution of forced convective cooling for vehicle-mounted LIDAR when vehicle is being driven. In addition, transient thermal behavior accounting for vehicle driving scenarios can allow engineers to determine impact of temperature transients and the time to reach a critical temperature condition. These simulation-driven analysis, from early prototyping stages, empowers LIDAR designers to account for various performance and life limiting factors in their design and optimization analysis.

In the next section some of the typical thermal design options will be explored for a solid-state LIDAR system.

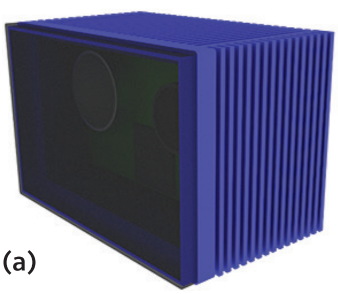
Solid-state LIDAR design exploration

Consider the notional solid-state LIDAR system that dissipates about 7W of heat which is distributed over three stacked printed circuit boards shown in figure 3. The maximum power IC power dissipation is 1.5W for the two components located on the rear printed circuit board (top as shown in figure 3) and are referenced as the critical components. IC components in a thermal design can be terms as critical for a number of reasons which include, high power dissipation, high power density, or restrictive temperature limit. Critical ICs in a LiDAR thermal design could be any SoC or temperature sensitive sensor. Even at relatively low power dissipations without the proper thermal design the device performance can be limited with reduced reliability.

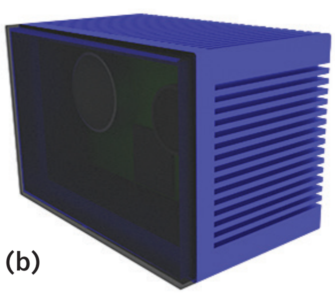
Figure 3: LIDAR printed circuit boards.

LIDAR enclosure design considerations

The heat generated from the LIDAR components is convected and radiated from the external enclosure surfaces. When transferring heat through convection from a solid surface to a fluid, total surface area in contact with the fluid plays a critical role. Design of this additional surface area in the device is highly dependent on the requirements for LIDAR integration in a vehicle. If the LIDAR is positioned such that it doesn't benefit from the airflow caused by vehicle movement then fins aligned vertically with gravity as shown in figure 4a would typically be the recommended orientation. When the LIDAR system is exposed to forced air from the environment the fins would be aligned with the predominant flow direction. In this example the air movement is left to right resulting in the fin alignment shown in figure 4b.



(a)



(b)

Figure 4: Lidar enclosure design with (a) side fins aligned vertically with gravity, (b) aligned with system airflow.

Whether the airflow is caused by buoyancy or external forces the fins are best designed for the specific system. Simcenter's design-centric thermal simulation allows parameters such as fin count, fin thickness, and fin length to be optimized while either directly modeling or including the effects of the overall system.

Depending on the air speed across the fins, and the surrounding radiating surfaces, thermal radiation from the external surfaces may be a significant mode of heat transfer. If a LIDAR is placed near components at high temperatures, it will absorb additional heat which will ultimately result in the LIDAR operating at elevated temperatures.

Because the heat transfer from the LIDAR is influenced directly by how and where it is integrated in a vehicle, it is advisable to perform the enclosure thermal design while including the vehicle integration location and associated effects. When designing the fins the thermal performance is a primary concern but must be considered along with the weight, cost, and manufacturability of the enclosure design.

LIDAR electronics thermal design

Appropriate thermal management of electronics board and critical ICs in the board is critical to ensure performance and reliability. Small form factors, as desired for automotive use, even for low power LIDARS can pose significant challenges for electronics thermal design. Heat generated from the internal LIDAR components is convected, conducted, and radiated to the enclosure internal surfaces. Heat transfer effectiveness for critical IC components can be improved through increasing heat transfer surface area or by adding new conduction paths.

Placing a heatsink or heat spreader on a device can lower the component temperature. Figure 5a shows a heat spreader mounted on the two 1.5W devices. Due to the size constraints of a solid-state LIDAR, addition of any significant heat transfer surface area via a heatsink is problematic. It is a design alternative worth exploring when only a small improvement in performance is needed.

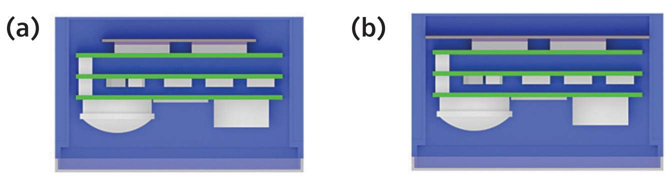


Figure 5: Solid-state LIDAR electronics layout with (a) internal heat spreaders, (b) conduction path from IC to enclosure for critical components.

When a significant reduction in temperature is needed the addition of a direct conduction path to the outer enclosure is a recommended design alternative. Thermal conduction in solids such as Aluminum is much more efficient that convection (and conduction) through air. A conduction path from IC components to the enclosure, as shown in figure 5b, will result in the component temperatures operating at temperatures much closer to the enclosure temperature. The temperature reduction is influenced by a number of factors including the IC heat dissipation and the thermal resistances between the IC and enclosure. While this design option has the benefit of reducing the IC temperature substantially, it can also lead to an elevated enclosure temperature.

Solid-state LIDAR, described above, was simulated to explore the relative benefits of the conduction and enclosure fin strategies. Simulations were done for a 35°C natural convection environment. The enclosure was assumed to have an emissivity of 0.9, for radiative heat transfer. Table 1 summarizes thermal simulation results for solid-state LIDAR with the design options considered in this example. The critical IC temperature refers to the 1.5W component on the rear board with the higher operating temperature. The results show that including the conduction path reduced the critical IC temperature by 50 percent, from 104.8°C to 66.5°C. This design change did result in an 18% enclosure temperature increase, from 57.4°C to 61.5°C. The addition of the conduction path reduced all of the temperatures with the LIDAR enclosure as shown in the figure 6 surface temperature plots. The results also indicate that the fins, in their current form, provide no significant benefit.

Design	A	B	C	D
External fins	None	None	Horizontal	Vertical
Direct conduction	No	Yes	Yes	Yes
Critical IC temperature [°C]	104.8	66.5	66.6	66.5
Enclosure temperature [°C]	57.4	61.5	61.7	61.5

Table 1: Solid-state LIDAR enclosure and critical IC temperature as a function of design variables.

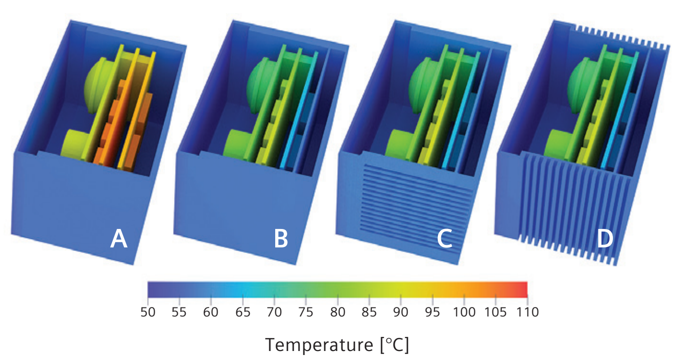


Figure 6: Surface temperature plots for LIDAR as a function of design variables.

LIDAR vehicle integration

While many thermal design parameters may be considered with the LIDAR in stand-alone scenario as shown in the previously described example, sensor designers must account for the effect of vehicle integration implications from early design stages. Vehicle integration introduces two important considerations for thermal design: 1) solar radiation load on LIDAR depending on its mounting location, and 2) additional active cooling due to forced convection while vehicle is being driven. Answers to questions regarding the expected amount of airflow or the influence of neighboring systems can only be answered by a thermal-airflow model that includes the additional information. Let's consider a scenario where a solid-state LIDAR (design C from figure 6) is mounted in the front grill of a vehicle, as shown in figure 7. Ambient temperature in this case is 35°C and for simplicity of analysis we are considering vehicle is driven at a constant speed of 10 m/s. An incident solar load of 300 W/m2 with 50% absorption was also included.

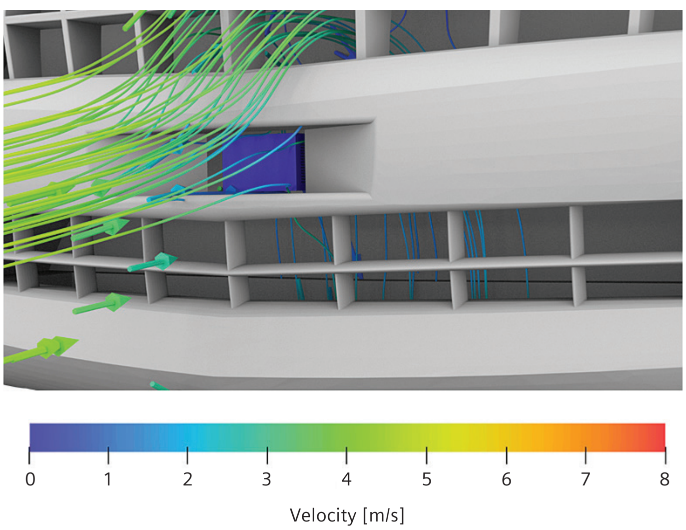


Figure 7: Front grill mounted Solid-State LIDAR [design C] model.

Figure 8 shows a cross section of the LIDAR with a speed contour and surface temperature plot. For clarity, vehicle body is not shown in this figure. Near the fin area there is about three m/s of airflow which provides enough convective cooling as seen by the enclosure surface temperatures slightly above the ambient temperature of 35°C. The internal component temperatures range from 45°C to 75°C. There was a reduction in critical IC temperature from 67°C, in the natural convection study, to 45°C when simulating in the 10 m/s environment. When not considering the environment in the simulation there is a risk of either over design, or under design. Either way there is a risk of uncertainty in the thermal design that can be avoided if the thermal design considers external influences.

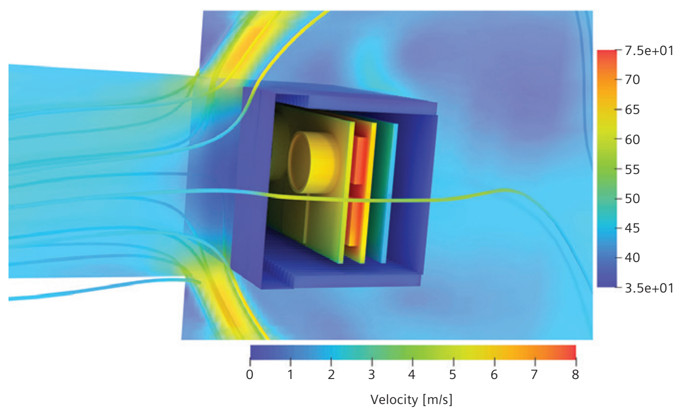


Figure 8: Front grill mounted Solid-State LIDAR model enlarged.

The Impact of solar radiation for front-grill mounted LIDAR was minimal. However, for LIDARs that are mounted on the vehicle roof or other areas directly exposed to sun, this can't be neglected. A wide range of analyses for LIDAR thermal behavior as a function of its mounting location can be easily carried out using the framework described here.

Testing autonomous vehicle functionality in extreme hot (for instance, Death Valley, Arizona) and cold (Minnesota winters) weather conditions is a critical part of vehicle verification and validation. To ensure LIDARs (and other sensors and autonomous functionality-enabling electronics) can function in extremely hot and cold weather conditions, thermal simulation of vehicle integrated LIDARs will be extremely useful for both sensor vendors and auto OEMs. Using the framework showcased in this section, engineers can simulate thermal behavior and its impact on vehicle functionality for any number of real-world traffic scenarios and avoid heavily relying on wind tunnel testing and/or full-vehicle testing.

Another benefit of thermal simulation of vehicle integrated LIDARs, as shown in this article, is that using the temperature response, sensor engineers can develop appropriate temperature compensation algorithms for LIDAR range and resolution estimates.

LIDAR integration in headlights and tail lights

In the last couple of years, solid-state LIDAR integration in headlights and tail lights have been proposed [6]. LIDAR integration in head or tail lights offers not just better vehicle aesthetics but also LIDAR protection from dust, dirt, water However, a unique set of challenges arise for LIDAR and headlight design. Integration challenges include heat from neighboring lamps, and condensation or icing on the headlight lens that will negatively impact LIDAR performance. LIDAR developers and headlight designers alike can leverage Simcenter's CAD-embedded headlight simulation capabilities [7, 8] to address these integration challenges. For instance, figure 9 shows a transient simulation for water condensation on exterior glass of an automotive LED headlight. Transients and non-uniform distribution of water (and similarly ice) film strongly depends on headlight design. In contrast to today's vehicle, transients of headlight defogging and de-icing has strong implications for autonomous vehicles with LIDAR integrated headlights. We'll discuss LIDAR integrated headlights design in a future white paper.

Figure 9: CAD-embedded automotive headlight simulation for transient defogging analysis.

Integration of thermal characterization testing with simulation with simulation for accurate predictions

A key challenge for accurate electronics thermal simulation is the lack of reliable thermal properties. We empower engineers to overcome this bottleneck by allowing them to seamlessly bring thermal characterization of electronics board components using Simcenter T3STER to electronics thermal simulation models. Simcenter T3STER is an advanced thermal tester for non-destructive thermal characterization of IC packages, LEDs and systems producing extensive thermal characteristics rapidly. Simcenter's electronics thermal models can be calibrated against Simcenter T3STER measurements through an automated process. Benchmarking electronics thermal simulation with this workflow against measured data has shown <0.5% error. For more information about experiments and simulation integrated workflow, please refer to a paper from Huawei in Therminic 2016 [9] and an on-demand webinar [10]. With the validated thermal model, the dynamic response of LIDARs (and other AV electronics), subject to a number of use case scenarios, could be explored well before prototypes are available.

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